

# Nucleon tensor charge and electric dipole moment

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## Abstract

The electric dipole moment (EDM), which violates both parity and time-reversal symmetries, is one of the most sensitive probes of new physics beyond the standard model. Nucleons as the main building blocks of the visible universe provide a natural laboratory for the exploration of additional  $CP$  violation sources to understand the baryogenesis mechanism. The nucleon tensor charge, which can be measured through semi-inclusive deep inelastic scattering (SIDIS) processes, is a fundamental QCD quantity that measures the transversely polarized quark number in a transversely polarized proton. It also plays as a weighting factor of the nucleon EDM contributed by quark EDMs. With a combination of nucleon EDM measurements and tensor charge extractions, we investigate the constraint on quark EDMs, and then the sensitivity to  $CP$  violating sources from new physics beyond the electroweak scale. We also estimate the impacts of future EDM and SIDIS experiments, which are expected to dramatically improve the sensitivity of the proton and neutron EDM measurement and the precision of the tensor charge extraction. We show that these experiments will lead to a much more stringent constraint on quark EDMs and thus a more sensitive probe of new physics models.

**Keywords:** Tensor charge, Electric dipole moment, CP violation

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## 1. Introduction

Symmetries play a central role in physics. Discrete symmetries, charge conjugate ( $C$ ), parity ( $P$ ), and time-reversal ( $T$ ), were believed to be conserved until the discovery of the parity violation in weak interactions suggested by Lee and Yang [1] and then measured in nuclear beta decays [2] and successive meson decays [3]. It is a cornerstone of the standard model (SM) in particle physics. Subsequently, the violation of the combination of charge conjugate and parity,  $CP$ , was discovered in neutral kaon decays [4] and also observed in  $B$ -meson and strange  $B$ -meson decays in recent years [5, 6, 7]. Although the Kobayash-Maskawa (KM) mechanism [8] provides a consistent and economical SM description of all observed  $CP$  violating phenomena in collider physics, the  $CP$  violating phase in the Cabibbo-Kobayashi-Maskawa (CKM) matrix is not enough to account for the observed asymmetry of matter and antimatter in the visible universe. Therefore, additional  $CP$  violation source is required, unless one accepts the fine tuning solution of the initial condition prior to the Big Bang.

Nucleons, as building blocks of more than 99% of the visible universe, are natural laboratories for the search of extra  $CP$  violating interactions. A permanent electric dipole moment (EDM) of any particle with a non-degenerate ground state violates both the parity and the time-reversal symmetries. Assuming the  $CPT$  invariance, which is a consequence of local quantum field theories with Lorentz invariance [9, 10, 11, 12], a nonvanishing EDM is a signal of  $CP$  violation. As the CKM complex phase requires the participation of three fermion generations, the EDM of light quarks is highly suppressed by the flavor changing interactions at the loop level, and hence the KM mechanism only results in an extremely small nucleon EDM [13, 14, 15]. Therefore, the nucleon EDM provides a complementary approach to high energy collider experiments for the search of beyond SM physics, and remains one of the most sensitive probes.

The history of nucleon EDM experiments can be traced back to the 1950s, and the first experiment was proposed by Purcell and Ramsey using the neutron-beam magnetic resonance method [16, 17]. The current upper limit on the neutron EDM from direct measurements is  $3.0 \times 10^{-26} e \cdot \text{cm}$  (90% C.L.) [18], which was obtained with ultra-cold

neutrons permeated in uniform electric ( $E$ ) and magnetic ( $B$ ) fields by measuring the Larmor precession frequency  $\nu$  given as

$$h\nu = |2\mu_n B \pm 2d_n E|, \quad (1)$$

where the sign ( $\pm$ ) represents parallel and anti-parallel electric and magnetic fields. Since the existence of an electric monopole overwhelms the dipole signal, the upper limit on the proton EDM is usually derived from the limit on the Hg atom EDM with the Schiff moment method [19]. The most recent measurement of the EDM of  $^{199}\text{Hg}$  atoms sets the upper limit on the mercury atom EDM to  $7.4 \times 10^{-30} e \cdot \text{cm}$  [20], which corresponds to an upper limit on the proton EDM of  $2.0 \times 10^{-25} e \cdot \text{cm}$  and an upper limit on the neutron EDM of  $2.1 \times 10^{-26} e \cdot \text{cm}$  [21].

Following the effective field theory, the effective Lagrangian that contributes to the nucleon EDM can be expressed up to dimension-six as [22]

$$\begin{aligned} \mathcal{L}_{\text{eff}} = & -\bar{\theta} \frac{g_s^2}{64\pi^2} \epsilon^{\mu\nu\rho\sigma} G_{\mu\nu}^a G_{\rho\sigma}^a - \frac{1}{2} \sum_q d_q \bar{\psi}_q i\sigma^{\mu\nu} \gamma_5 \psi_q F_{\mu\nu} - \frac{1}{2} \sum_q \tilde{d}_q \bar{\psi}_q i\sigma^{\mu\nu} t^a \psi_q G_{\mu\nu}^a \\ & + \frac{1}{6} d_W f^{abc} \epsilon^{\mu\nu\rho\sigma} G_{\mu\nu}^a G_{\rho\lambda}^b G_{\sigma}^{c\lambda} + \sum_{i,j,k,l} C_{ijkl} \bar{\psi}_i \Gamma \psi_j \bar{\psi}_k \Gamma' \psi_l, \end{aligned} \quad (2)$$

where  $g_s$  is the strong coupling constant,  $G_{\mu\nu}^a$  is the gluon field,  $F_{\mu\nu}$  is the electromagnetic field, and  $\psi_q$  is the quark field. The first term, a dimension-four operator, is allowed in the standard model as the QCD  $\theta$ -term, where the overall phase of the quark mass matrix is absorbed into  $\bar{\theta}$ . It could in principle generate large hadronic EDMs, but the upper limit on the neutron EDM constrains the coefficient to  $|\bar{\theta}| \leq 10^{-10}$ . The two dimension-five terms are respectively the quark EDM  $d_q$  and the quark chromoelectric dipole moment  $\tilde{d}_q$ . In order to restore the  $SU(2) \times U(1)$  symmetry above the electroweak scale, a Higgs field insertion is included in these two terms [23]. Therefore, they are essentially dimension-six operators, and are often in practice supplied by an insertion of the quark mass as  $m_q/\Lambda^2$ , where  $\Lambda$  represents a large mass scale. For consistency, other dimension-six operators, the three-gluon Weinberg operator and the four-fermion interactions, should also be introduced.

In this paper, we focus on the quark EDM term. Combining the upper limits on nucleon EDMs and the extractions of the nucleon tensor charge, we show the constraint on quark EDMs and thus new physics models. The impacts of future experiments are also discussed.

## 2. Tensor charge and quark EDM

The quark EDM contribution to the nucleon EDM can be expressed as

$$d_p = g_T^u d_u + g_T^d d_d, \quad (3)$$

$$d_n = g_T^d d_u + g_T^u d_d, \quad (4)$$

where the isospin symmetry is applied and the heavy flavor contribution is neglected. The coefficient  $g_T^{u,d}$  is the nucleon tensor charge, which is a fundamental QCD quantity defined by the matrix element of a local operator as

$$\langle p, \sigma | \bar{\psi}_q i\sigma^{\mu\nu} \psi_q | p, \sigma \rangle = g_T^q \bar{u}(p, \sigma) i\sigma^{\mu\nu} u(p, \sigma). \quad (5)$$

It measures the transverse spin carried by the quark in a transversely polarized proton. In the nonrelativistic quark model, the  $SU(6)$  spin-flavor symmetry gives the tensor charges as

$$g_T^u = \frac{4}{3}, \quad g_T^d = -\frac{1}{3}. \quad (6)$$

Due to the relativistic effect, the tensor charge reduces from the prediction of the naive quark model [24], and differs from the axial-vector charge, which represents the longitudinal spin carried by quarks in a longitudinally polarized proton. As shown in Figure 1, the tensor charge has been calculated in many phenomenological models [25, 26, 27, 28, 29, 30, 31, 32, 33, 34], and with some nonperturbative methods, such as the Dyson-Schwinger equation [35, 36] and lattice QCD simulations [37, 38, 39, 40, 41, 42].

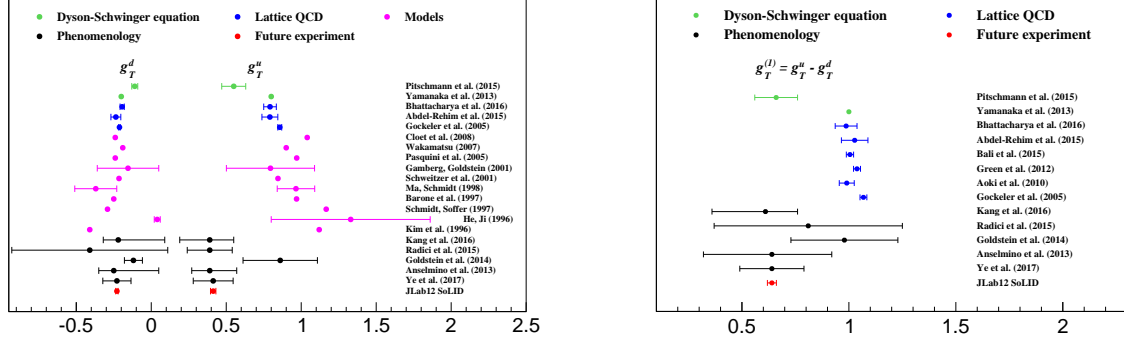


Figure 1: Tensor charge results. The left panel shows the values of  $u$  and  $d$  quark tensor charges, and the right panel shows the values of the isovector tensor charge. The green points are from Dyson-Schwinger equation calculations [35, 36], the blue points are from lattice QCD calculations [37, 38, 39, 40, 41, 42], the magenta points are from model calculations [25, 26, 27, 28, 29, 30, 31, 32, 33, 34], the black points are phenomenological extractions from data [44, 45, 46, 47, 48], and the red points are the projection of JLab-12GeV SoLID experiment [48] based on the most recent global analysis [44].

In the quark-parton model, the tensor charge is equal to the first moment of the quark transversity distribution,

$$g_T^q = \int_0^1 dx [h_1^q(x) - h_1^{\bar{q}}(x)], \quad (7)$$

where  $x$  is the longitudinal momentum fraction carried by the quark. The transversity  $h_1(x)$  as a leading-twist parton distribution function is interpreted as the net density of transversely polarized quarks in a transversely polarized proton. Unlike the helicity distribution that measures the density of longitudinally polarized quarks in a longitudinally polarized nucleon, the transversity distribution is a chiral-odd quantity, which results in a simpler QCD evolution effect without mixing with gluons and is valence quark dominant. However, the chiral-odd property makes it decouple at the leading-twist from the inclusive deep-inelastic scattering (DIS) process, which is usually the most efficient approach to measure parton distributions, and hence it should be measured by coupling to another chiral-odd quantity. Semi-inclusive DIS (SIDIS) is one of the processes that can be used to measure transversity distributions. At the leading twist, the transversity distribution can be extracted from a transverse target single spin asymmetry, the Collins asymmetry, which arises from the convolution of the transversity distribution and the Collins fragmentation function within the framework of the transverse momentum dependent (TMD) factorization. It can also be measured in the collinear factorization through the di-hadron process [43] by coupling to the di-hadron fragmentation function. The tensor charge values from some recent global analyses are shown in Figure 1.

Following Eqs. (3) and (4), we can obtain the constraint on quark EDMs by combining the upper limits on nucleon EDMs and the measured tensor charges. To have quantitative estimations, we take the upper limits on nucleon EDMs derived from the most recent measurement of  $^{199}\text{Hg}$  EDM [20] with the Schiff moment method [19] as

$$|d_p| \leq 2.0 \times 10^{-25} e \cdot \text{cm}, \quad |d_n| \leq 2.1 \times 10^{-26} e \cdot \text{cm}. \quad (8)$$

For the tensor charge, we use the values from a recent global analysis [44, 48]

$$g_T^u = 0.413 \pm 0.133, \quad g_T^d = -0.229 \pm 0.094. \quad (9)$$

The constraints on quark EDMs are shown in Figure 2. Combining the limits on the proton EDM and the neutron EDM, one can get the upper limits on  $u$  and  $d$  quark EDMs respectively. The results are shown in Table 1.

### 3. Sensitivity to new physics and future experiments

Since the SM CKM complex phase produces an extremely small quark EDM [13], which can be viewed as a background within the experimental precisions at present and even in the next ten years, the quark EDM is a very sensitive

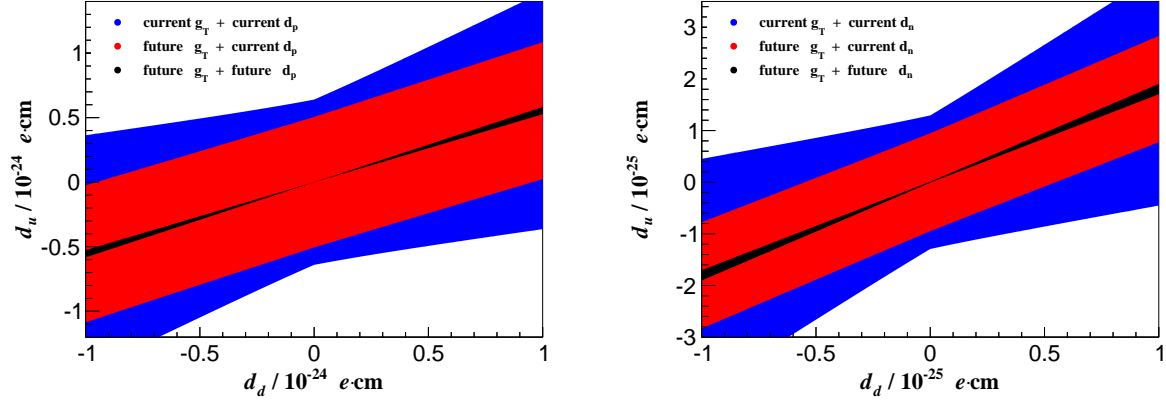


Figure 2: Constraints on quark EDMs with the upper limits on nucleon EDMs and the tensor charge extractions. The left panel shows the constraints by the upper limit on the proton EDM, and the right panel shows the constraints by the upper limit on the neutron EDM. The blue bands are the current constraints with the tensor charge extraction in Eq. (9) and the current proton EDM limit  $2.0 \times 10^{-25} e \cdot \text{cm}$  or the current neutron EDM limit  $2.1 \times 10^{-26} e \cdot \text{cm}$ , the red bands are the constraints with the future tensor charge extraction, Eq. (14), and the current proton or neutron EDM limit, and the black bands are the constraints with the future tensor charge extraction and the future proton EDM limit  $2.0 \times 10^{-29} e \cdot \text{cm}$  or the future neutron EDM limit  $2.1 \times 10^{-28} e \cdot \text{cm}$ .

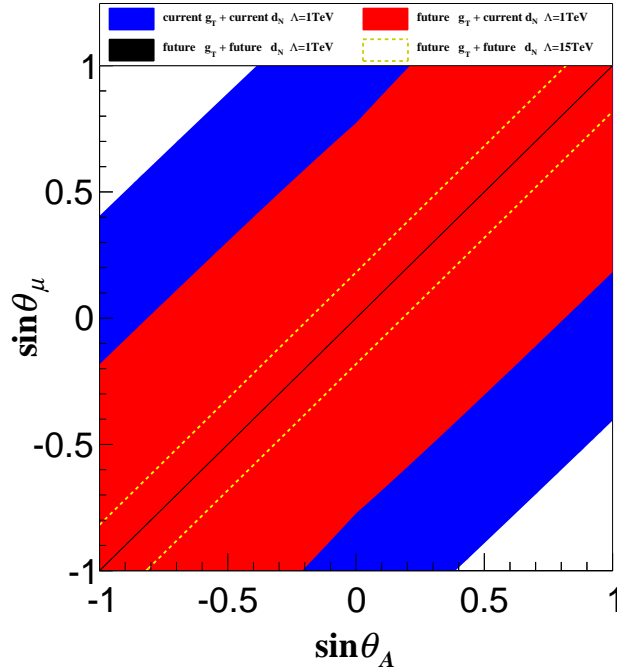


Figure 3: Constraint of the parameter space of supersymmetric models. The constraint is obtained with the  $u$  and  $d$  quark EDM limits. The  $u$  quark mass is set at  $2.2 \text{ MeV}$ , and the  $d$  quark mass is set at  $4.7 \text{ MeV}$  as in Ref. [51]. The strong coupling constant  $\alpha_s$  is taken from Ref. [52] as  $0.41\pi$  at  $1 \text{ GeV}$  scale. The three bands are plotted at  $\Lambda = 1 \text{ TeV}$  scale. The blue band shows the current constraint, the red band shows the constraint with the future tensor charge measurement, Eq. (14), and the black band shows the constraint with the future tensor charge measurement and the future nucleon EDM experiments. The dashed yellow lines show the constraint with future tensor charge measurement and the future nucleon EDM experiments at  $\Lambda = 15 \text{ TeV}$  scale.

Table 1: Upper limits on quark EDMs. All EDM values are given as upper limits. The current limits are shown in the first row, and the future expected limits are shown from the second row.

$g_T^u$	$g_T^d$	$ d_p  (e \cdot \text{cm})$	$ d_n  (e \cdot \text{cm})$	$ d_u  (e \cdot \text{cm})$	$ d_d  (e \cdot \text{cm})$
$0.413 \pm 0.133$	$-0.229 \pm 0.094$	$2.0 \times 10^{-25}$	$2.1 \times 10^{-26}$	$1.3 \times 10^{-24}$	$1.0 \times 10^{-24}$
$0.413 \pm 0.018$	$-0.229 \pm 0.008$	$2.0 \times 10^{-25}$	$2.1 \times 10^{-26}$	$8.0 \times 10^{-25}$	$5.2 \times 10^{-25}$
$0.413 \pm 0.018$	$-0.229 \pm 0.008$	$2.0 \times 10^{-25}$	$2.1 \times 10^{-28}$	$7.6 \times 10^{-25}$	$4.4 \times 10^{-25}$
$0.413 \pm 0.018$	$-0.229 \pm 0.008$	$2.0 \times 10^{-29}$	$2.1 \times 10^{-26}$	$4.6 \times 10^{-26}$	$8.0 \times 10^{-26}$
$0.413 \pm 0.018$	$-0.229 \pm 0.008$	$2.0 \times 10^{-29}$	$2.1 \times 10^{-28}$	$5.4 \times 10^{-28}$	$8.4 \times 10^{-28}$

probe of new physics. As mentioned in the introduction, the quark EDM is suppressed by the quark mass [23] for new physics beyond the electroweak scale. Thus one expects the magnitude of quark EDM as  $d_q \sim em_q/(4\pi\Lambda^2)$  [50], where  $\Lambda$  represents the scale of new physics. According to the analysis in the previous section, the current limit on quark EDMs is about  $10^{-24} e \cdot \text{cm}$ . With the light quark mass of several MeVs, the current limit has the sensitivity to new physics around 1 TeV, which is directly reached by the LHC.

Moreover, if the  $\mathcal{CP}$  violating source is flavor-diagonal as in some new physics models, we may further assume that the quark EDM  $d_q$  is proportional to  $e_q m_q$  at the leading order. Then the ratio between  $u$  and  $d$  quark EDMs is

$$\frac{d_u}{d_d} = \frac{e_u m_u}{e_d m_d}. \quad (10)$$

In this case, we can have a more stringent constraint on quark EDMs. With the light quark mass ratio  $m_u/m_d = 0.38 \sim 0.58$  in Ref. [51], we obtain the limit as

$$|d_d| \leq 4.1 \times 10^{-26}. \quad (11)$$

Then the sensitivity to the flavor-diagonal source can reach a higher energy scale. Actually, only one limit on the EDM of the nucleon, either proton or neutron, is needed to derive the quark EDM limit with this assumption. As the current limit on the neutron EDM is one order smaller than that on the proton EDM, the constraint above is from the neutron EDM limit. However, the assumption applied here is not generally true, and hence such a sensitivity is only expected when the proton EDM experiment reaches the precision at the same level of the neutron EDM measurement.

As a specific example, we estimate the constraint of the  $\mathcal{CP}$  violating parameters in supersymmetric extensions of the SM. The quark EDM induced by the additional  $\mathcal{CP}$  violation phases can be expressed as [50]

$$d_q = \frac{e_q m_q}{\Lambda^2} \frac{e\alpha_s}{18\pi} \left[ \sin \theta_\mu (\tan \beta)^\pm - \sin \theta_A \right], \quad (12)$$

where  $\theta_\mu$  and  $\theta_A$  are the phases that parametrize the  $\mathcal{CP}$  violation,  $\tan \beta$  is the ratio between the two Higgs vacuum expectation values, and the plus-minus sign corresponds to the  $d$  or  $u$  quark respectively. With the upper limits on  $u$  and  $d$  quark EDMs, the two  $\mathcal{CP}$  violation phase parameters are constrained by

$$\sin^2 \theta_\mu = \left( \sin \theta_A - \frac{3d_d}{em_d} \frac{18\pi\Lambda^2}{\alpha_s} \right) \left( \sin \theta_A + \frac{3d_u}{2em_u} \frac{18\pi\Lambda^2}{\alpha_s} \right). \quad (13)$$

The result is shown in Figure 3.

In order to probe new physics at a higher energy scale or to constrain the parameter space of some particular model to a more stringent level, it is required to improve the precision of both the tensor charge and the nucleon EDM measurements. The proposed SIDIS program at 12 GeV upgraded Jefferson Lab, particularly those with the SoLID [49], aims to have unprecedented precision measurements of quark three-dimensional polarized distributions. Therefore a precise determination of the tensor charge is expected. According to a recent quantitative analysis [48], the SoLID SIDIS experiments will improve the precision of the tensor charge by one order of magnitude compared to the current knowledge. An estimation based on the global analysis [44] gives the SoLID projection [48], shown in Figure 1, as

$$g_T^u = 0.413 \pm 0.018, \quad g_T^d = -0.229 \pm 0.008. \quad (14)$$

On the other hand, the sensitivity of neutron EDM measurements is expected to be improved by two orders of magnitude, *i.e.* to the level of  $10^{-28} e \cdot \text{cm}$  [53]. The proposed storage ring proton EDM experiment is expected to improve

the sensitivity to  $10^{-29} e \cdot \text{cm}$  [54]. To estimate the impacts of these experiments, we adopt the future proton EDM limit as  $2.0 \times 10^{-29} e \cdot \text{cm}$ , the future neutron EDM limit as  $2.1 \times 10^{-28} e \cdot \text{cm}$ , and the future tensor charge extractions in Eq. (14). As shown in Figure 2 and Table 1, the combination of these experiments will improve the limit on quark EDMs by two to three orders of magnitude compared with our current knowledge. Therefore we will be able to probe new physics beyond 10 TeV scale to about 30 TeV scale. The corresponding constraint on the parameter space of the supersymmetric model is shown in Figure 3 at 15 TeV scale.

#### 4. Summary

We investigate the constraint on quark EDMs by combining the nucleon EDM measurement and the tensor charge measurement. With the present sensitivities of the proton and neutron EDM experiments and the precision of current tensor charge extractions, we obtain the upper limit on quark EDMs about  $10^{-24} e \cdot \text{cm}$  for both  $u$  and  $d$  quarks. It corresponds to a probe of new physics up to the energy scale of 1 TeV, which is directly reached by the LHC. As an example, we estimate the constraint on the parameter space of a supersymmetric model as discussed in [50].

In the next ten years, both the sensitivity of nucleon EDM experiments and the precision of tensor charge extractions are expected to be dramatically improved. The planned SIDIS experiments at JLab will improve the uncertainty of the determination of the tensor charge by one order of magnitude [49, 48]. The next generation neutron EDM experiments aim to improve the precision to  $10^{-28} e \cdot \text{cm}$  [53]. The proposed storage ring proton EDM experiment is expected to reach a sensitivity of  $10^{-29} e \cdot \text{cm}$  [54]. All these experiments will make quark EDM a more sensitive probe of new physics models and reach the scale around 15 TeV, which is above the LHC energy. Therefore it will help us explore the new source of  $C\mathcal{P}$  violating effects and hence the baryogenesis of our universe.

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